REPORT DOCUMENTATION PAGE

Form Approved OMB NO. 0704-0188

1. REPORT DATE (DD-MM-YYYY)	2. REPORT TYPE	3. DATES COVERED (From - To)
05-08-2016	Final Report	1-Sep-2011 - 31-Aug-2016

4. TITLE AND SUBTITLE
From nanoscale systems to ultracold atoms and molecules, and back

5a. CONTRACT NUMBER
W911NF-11-1-0433

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER
611102

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

6. AUTHORS
Pierre Meystre

7. PERFORMING ORGANIZATION NAMES AND ADDRESSES
University of Arizona
P.O. Box 210158, Rm 510

Tucson, AZ 85721 -0158

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS (ES)
U.S. Army Research Office
P.O. Box 12211
Research Triangle Park, NC 27709-2211

10. SPONSOR/MONITOR'S ACRONYM(S)
ARO

11. SPONSOR/MONITOR'S REPORT NUMBER(S)
60612-PH.34

12. DISTRIBUTION AVAILIBILITY STATEMENT
Approved for Public Release; Distribution Unlimited

13. SUPPLEMENTARY NOTES
The views, opinions and/or findings contained in this report are those of the author(s) and should not contrued as an official Department of the Army position, policy or decision, unless so designated by other documentation.

14. ABSTRACT
We carried out a comprehensive program in atomic, molecular and optical physics that also has the potential to lead to significant advantages in quantum metrology, the emerging field of quantum acoustics, and quantum thermodynamics. This project lies at the boundary between two fields that have witnessed extraordinary progress in the last few years. The first is ultracold atomic science and the second is quantum optomechanics, this latter area relying significantly on major advances in nanoscience and nanofabrication. We can expect significant science and

15. SUBJECT TERMS
quantum optics, quantum optomechanics, nonclassical fields, ultracold sicence, quantum acoustics, quantum metrology, quntum themodynamics, quantum heat engines

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	15. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			Pierre Meystre
UU	UU	UU	UU		19b. TELEPHONE NUMBER
					520-621-4651

Standard Form 298 (Rev 8/98)
Prescribed by ANSI Std. Z39.18

Report Title

From nanoscale systems to ultracold atoms and molecules, and back

ABSTRACT

We carried out a comprehensive program in atomic, molecular and optical physics that also has the potential to lead to significant advantages in quantum metrology, the emerging field of quantum acoustics, and quantum thermodynamics. This project lies at the boundary between two fields that have witnessed extraordinary progress in the last few years. The first is ultracold atomic science and the second is quantum optomechanics, this latter area relying significantly on major advances in nanoscience and nanofabrication. We can expect significant science and engineering applications to result from the merging of these two fields, using in particular hybrid arrangements consisting of optomechanical nanoscale devices operating deep in the quantum regime and coupled to atoms, molecules, artificial atoms, or quantum degenerate atomic systems. Promising directions include the quantum control of mechanical devices by atomic systems and new approaches to quantum metrology. Quantum optomechanical systems may also provide a deeper understanding of the quantum-classical interface and of the fundamental physics of decoherence, and may help shed light on the foundations of thermodynamics at the quantum level, including e.g. the role of quantum correlations and the impact of quantum measurement backaction on the efficiency of heat engines. This may in the future result in nano-engineering applications such as quantum heat pumps and autonomous quantum heat engines.

Enter List of papers submitted or published that acknowledge ARO support from the start of the project to the date of this printing. List the papers, including journal references, in the following categories:

(a) Papers published in peer-reviewed journals (N/A for none)

Received		Paper
07/10/2012	1.00	S. Steinke, P. Meystre. Role of quantum fluctuations in the optomechanical properties of a Bose-Einstein condensate in a ring cavity, Physical Review A, (8 2011): 0. doi: 10.1103/PhysRevA.84.023834
07/10/2012	7.00	Markus Aspelmeyer, Pierre Meystre, Keith Schwab. Quantum optomechanics, Physics Today, (2012): 0. doi: 10.1063/PT.3.1640
07/10/2012	6.00	Keye Zhang, Pierre Meystre, Weiping Zhang. Role Reversal in a Bose-Condensed Optomechanical System, Physical Review Letters, (6 2012): 0. doi: 10.1103/PhysRevLett.108.240405
07/10/2012	5.00	L. Buchmann, L. Zhang, A. Chiruvelli, P. Meystre. Macroscopic Tunneling of a Membrane in an Optomechanical Double-Well Potential, Physical Review Letters, (5 2012): 0. doi: 10.1103/PhysRevLett.108.210403
07/10/2012	4.00	H. Seok, L. Buchmann, S. Singh, S. Steinke, P. Meystre. Generation of mechanical squeezing via magnetic dipoles on cantilevers, Physical Review A, (3 2012): 0. doi: 10.1103/PhysRevA.85.033822
07/10/2012	3.00	P. Meystre. Cool Vibrations, Science, (08 2011): 0. doi: 10.1126/science.1208322
07/10/2012	2.00	S. Singh, S. Steinke, M. Tasgin, P. Meystre, K. Schwab, M. Vengalattore. Quantum-measurement backaction from a Bose-Einstein condensate coupled to a mechanical oscillator, Physical Review A, (8 2011): 0. doi: 10.1103/PhysRevA.84.023841
07/15/2013	8.00	S. Singh, H. Jing, E. M. Wright, P. Meystre. Quantum-state transfer between a Bose-Einstein condensate and an optomechanical mirror, Physical Review A, (08 2012): 0. doi: 10.1103/PhysRevA.86.021801
07/15/2013	13.00	Pierre Meystre. A short walk through quantum optomechanics, Annalen der Physik, (03 2013): 0. doi: 10.1002/andp.201200226
07/15/2013	12.00	L. F. Buchmann, H. Jing, C. Raman, P. Meystre. Optical control of a quantum rotor, Physical Review A, (03 2013): 0. doi: 10.1103/PhysRevA.87.031601
07/15/2013	11.00	Huatang Tan, Gaoxiang Li, P. Meystre. Dissipation-driven two-mode mechanical squeezed states in optomechanical systems, Physical Review A, (03 2013): 0. doi: 10.1103/PhysRevA.87.033829
07/15/2013	10.00	H. Seok, L. F. Buchmann, S. Singh, P. Meystre. Optically mediated nonlinear quantum optomechanics, Physical Review A, (12 2012): 0. doi: 10.1103/PhysRevA.86.063829
07/24/2015	22.00	Francesco Bariani, Keye Zhang, Pierre Meystre. Theory of an optomechanical quantum heat engine, Physical Review A, (8 2014): 0. doi: 10.1103/PhysRevA.90.023819
07/24/2015	25.00	E. M. Wright, H. Seok, P. Meystre. Dynamic stabilization of an optomechanical oscillator, Physical Review A, (10 2014): 0. doi: 10.1103/PhysRevA.90.043840

07/24/2015 24.00 Keye Zhang, Francesco Bariani, Ying Dong, Weiping Zhang, Pierre Meystre. Proposal for an Optomechanical Microwave Sensor at the Subphoton Level,
Physical Review Letters, (3 2015): 0. doi: 10.1103/PhysRevLett.114.113601

07/24/2015 23.00 F. Bariani, S. Singh, L. F. Buchmann, M. Vengalattore, P. Meystre. Hybrid optomechanical cooling by atomic,
Physical Review A, (9 2014): 0. doi: 10.1103/PhysRevA.90.033838

07/25/2014 14.00 Weiping Zhang, Keye Zhang, Pierre Meystre. Back-action-free quantum optomechanics with negative-mass Bose-Einstein condensates,
Physical Review A, (10 2013): 43632. doi: 10.1103/PhysRevA.88.043632

07/25/2014 15.00 Huatang Tan, F. Bariani, Gaoxiang Li, P. Meystre. Generation of macroscopic quantum superpositions of optomechanical oscillators by dissipation,
Physical Review A, (08 2013): 23817. doi: 10.1103/PhysRevA.88.023817

07/25/2014 16.00 E. M. Wright, P. Meystre, L. F. Buchmann. Phase conjugation in quantum optomechanics,
Physical Review A, (10 2013): 41801. doi: 10.1103/PhysRevA.88.041801

07/25/2014 17.00 S. Steinke, S. Singh, P. Meystre, K. Schwab, M. Vengalattore. Quantum backaction in spinor-condensate magnetometry,
Physical Review A, (12 2013): 0. doi: 10.1103/PhysRevA.88.063809

07/25/2014 18.00 H. Seok, L. F. Buchmann, E. M. Wright, P. Meystre. Multimode strong-coupling quantum optomechanics,
Physical Review A, (12 2013): 63850. doi: 10.1103/PhysRevA.88.063850

07/25/2014 19.00 F. Bariani, J. Otterbach, Huatang Tan, P. Meystre. Single-atom quantum control of macroscopic mechanical oscillators,
Physical Review A, (01 2014): 11801. doi: 10.1103/PhysRevA.89.011801

07/25/2014 20.00 Keye Zhang, Francesco Bariani, Pierre Meystre. Quantum Optomechanical Heat Engine,
Physical Review Letters, (04 2014): 150602. doi: 10.1103/PhysRevLett.112.150602

07/25/2014 21.00 A. A. Clerk, K. C. Schwab, J. Suh, A. J. Weinstein, C. U. Lei, E. E. Wollman, S. K. Steinke, P. Meystre. Mechanically detecting and avoiding the quantum fluctuations of a microwave field,
Science, (05 2014): 0. doi: 10.1126/science.1253258

TOTAL: **24**

Number of Papers published in peer-reviewed journals:

(b) Papers published in non-peer-reviewed journals (N/A for none)

Received Paper

TOTAL:

Number of Papers published in non peer-reviewed journals:

(c) Presentations

1. P. Meystre, “Quantum optomechanics, thermodynamics, and heat engines,” invited talk, Frontiers in Quantum Optics 2015 – Symposium in the honor of the Landmark Birthdays of Roy J. Glauber and Maciej Lewenstein,” Castelldefels (Barcelona), Spain (2015).

2. P. Meystre, “Fifty(two) years of quantum optics,” invited talk, Glauber 90th – A Symposium. Harvard University, Cambridge, MA (2015).

3. P. Meystre, "Quantum optomechanics and quantum heat engines," Boston IEEE Photonics Society, Lexington, MA (2015).

Number of Presentations: 3.00

Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received	Paper

TOTAL:

Number of Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received		Paper
07/15/2013	9.00	E. M. Wright, M. Mazilu, S. Singh, K. Dholakia, P. Meystre, Kishan Dholakia, Gabriel C. Spalding. Theory and simulation of an optical spring mirror, SPIE NanoScience + Engineering. 12-AUG-12, San Diego, California, USA. : ,

TOTAL: 1

Number of Peer-Reviewed Conference Proceeding publications (other than abstracts):

(d) Manuscripts

Received	Paper
07/27/2016 26.00	Ying Dong, Keye Zhang, Francesco Bariani, Pierre Meystre. Work measurement in a quantum optomechanical heat engine, PHYSICAL REVIEW A (05 2015)
07/27/2016 27.00	Ying Dong, F. Bariani, P. Meystre. Phonon cooling by an optomechanical heat pump, P H Y S I C A L R E V I EW L E T T E R S (07 2015)
TOTAL:	**2**

Number of Manuscripts:

Books

Received	Book
TOTAL:	

Received	Book Chapter
07/28/2016 31.00	. Atom Optics in a Nutshell, : Springer Verlag, (2016)
07/28/2016 32.00	. Quantum optics, thermodynamics, and heat engines, : Oxford University Press, (2016)
TOTAL:	**2**

Patents Submitted

Patents Awarded

Awards

Appointed Editor in Chief of the American Physical Society

Graduate Students

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Names of Post Doctorates

NAME	PERCENT_SUPPORTED
Francesco Bariani	0.18
Swati Singh	0.71
Steven Steinke	0.37
FTE Equivalent:	**1.26**
Total Number:	**3**

Names of Faculty Supported

NAME	PERCENT_SUPPORTED	National Academy Member
Pierre Meystre	0.04	No
FTE Equivalent:	**0.04**	
Total Number:	**1**	

Names of Under Graduate students supported

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Student Metrics

This section only applies to graduating undergraduates supported by this agreement in this reporting period

The number of undergraduates funded by this agreement who graduated during this period: 0.00

The number of undergraduates funded by this agreement who graduated during this period with a degree in science, mathematics, engineering, or technology fields:...... 0.00

The number of undergraduates funded by your agreement who graduated during this period and will continue to pursue a graduate or Ph.D. degree in science, mathematics, engineering, or technology fields:...... 0.00

Number of graduating undergraduates who achieved a 3.5 GPA to 4.0 (4.0 max scale):...... 0.00

Number of graduating undergraduates funded by a DoD funded Center of Excellence grant for Education, Research and Engineering:...... 0.00

The number of undergraduates funded by your agreement who graduated during this period and intend to work for the Department of Defense 0.00

The number of undergraduates funded by your agreement who graduated during this period and will receive scholarships or fellowships for further studies in science, mathematics, engineering or technology fields:...... 0.00

Names of Personnel receiving masters degrees

NAME

Total Number:

Names of personnel receiving PHDs

NAME
HyoJun Seok

Total Number: 1

Names of other research staff

NAME	PERCENT_SUPPORTED

FTE Equivalent:
Total Number:

Sub Contractors (DD882)

Inventions (DD882)

Scientific Progress

1. Introduction

Broadly speaking, quantum optomechanics provides a universal tool to achieve the quantum control of mechanical motion. It does that in devices spanning a vast range of parameters, with mechanical frequencies from a few Hertz to GHz, and with masses from 10^{-20} g to several kilos. At a fundamental level, it offers a route to determine and control the quantum state of truly macroscopic objects and paves the way to experiments that may lead to a more profound understanding of quantum mechanics; and from the point of view of applications, quantum optomechanical techniques in both the optical and microwave regimes will provide motion and force detection near the fundamental limit imposed by quantum mechanics.

Many of the underlying ideas of quantum optomechanics can be traced back to the study of proposed interferometric gravitational wave detectors in the 1970s and 1980s (and which resulted to the first direct detection of gravitational waves originating from the collision of massive blackholes by the LIGO gravitational wave antennas in 2015.) In parallel to these kilometer-size systems, the advances in optoechanics of the last few years have relied largely on two additional developments: From the top down, it is the availability of advanced micromechanical and nanomechanical devices capable of probing extremely tiny forces, often with spatial resolution at the atomic scale. And from the bottom-up, we have gained a detailed understanding of the mechanical effects of light and how they can be exploited in laser trapping and cooling. These developments have opened a path to the realization of macroscopic mechanical systems that operate deep in the quantum regime, with no significant thermal noise remaining. As a result, they offer both knowledge and control of the quantum state of a macroscopic object, and remarkable increases in sensitivity, precision, and accuracy in the measurement of feeble forces and fields.

In many cases such measurements amount to the detection of exceedingly small displacements, and in that context the remarkable potential for functionalization of opto- and electromechanical devices is particularly attractive. Their motional degree (s) of freedom can be coupled to a broad range of other physical systems, including photons via radiation pressure from a reflecting surface, spin(s) via coupling to a magnetic material, electric charges via the interaction with a conducting surface, etc. In that way, the mechanical element can serve as a universal transducer or intermediary that enables the coupling between otherwise incompatible systems.

2. Toward nonlinear quantum optomechanics

Within this general context, an early highlight of our research in the last 5 years has been the theoretical prediction that it is possible to achieve a coherent quantum coupling between a quantum degenerate atomic system and a mechanical oscillator mediated by an optical field. In particular we have shown that under conditions where the optical field can be adiabatically eliminated one can achieve high fidelity quantum state transfer between a momentum side mode of the condensate and the oscillating end-mirror. This is of particular interest because of the exquisite control that can be achieved in preparing many-body quantum states in Bose condensates, and also, conversely, because high-precision magnetometry can be achieved in spinor condensates. Achieving quantum coherent coupling between systems as disparate as condensates and nanoscale oscillators therefore paves the way for a number of applications in basic science and quantum metrology.

Expanding on this work, we next turned our attention to the optomechanical interaction of several mechanical modes with a single quantized cavity field mode for both the cases of linear and of quadratic coupling, a first step toward the development of nonlinear optomechanics. We considered specifically the optomechanical interaction of several mechanical modes with a single quantized cavity field mode for linear and quadratic coupling, focusing specifically on situations where the optical dissipation is the dominant source of damping, in which case the optical field can be adiabatically eliminated, resulting in effective multimode interactions between the mechanical modes. In the case of linear coupling, the coherent contribution to the interaction can be exploited e.g. for quantum state swapping protocols, while the incoherent part leads to significant modifications of cold damping and the optical spring effect from the more familiar single-mode situation. Quadratic coupling can likewise result in a wealth of possible effective interactions including the analogs of second-harmonic generation and four-wave mixing in nonlinear optics, with specific forms depending sensitively on the sign of the coupling. We applied these ideas to several concrete examples such as e.g. phononic four-wave mixing and phase conjugation.

In that latter case we analyzed in some detail the phase conjugate coupling of a pair of optomechanical oscillator modes driven by the time-dependent beat-note of a two-color optical field, and found that the dynamics of the direct and phase conjugate modes exhibit familiar time-reversed qualities, leading in the classical limit to opposite sign temperatures for the modes in the classical regime of operation. In the quantum regime, however, these features are limited by quantum noise. We predict that this behavior should be measurable in a hybrid configuration by read-out of the oscillator via a qubit (more on hybrid systems later on.) As a potential application of this system in sensing, we also discussed a protocol applying phase-conjugate swaps to cancel or reduce external forces on the system.

In other examples of multimode optomechanics we proposed two quantum optomechanical arrangements that permit the dissipation-enabled generation of steady two-mode mechanical squeezed states. In a first setup, the mechanical oscillators are placed in a two-mode optical resonator while in the second setup the mechanical oscillators are located in two coupled single-mode cavities. We showed analytically that for an appropriate choice of the pump parameters, the two mechanical oscillators can be driven by cavity dissipation into a stationary two-mode squeezed vacuum, provided that mechanical damping remains negligible. We also proposed a scheme that exploits the combined effects of nonlinear dynamics and dissipation to generate macroscopic quantum superpositions in massive optomechanical oscillators. The effective degenerate three-wave mixing interaction between the mechanical and optical cavity modes, together with cavity dissipation, can result in the existence of such dark macroscopic superpositions.

3. Hybrid systems and optomechanical cooling

I already mentioned the potential of functionalization of optomechanical systems that can be achieved by coupling them to a broad range of other physical systems. As a specific example we have investigated a number of properties and potential applications of such a hybrid quantum system consisting of a cavity optomechanical device optically coupled to an ultracold quantum gas. We showed that the dispersive properties of the ultracold gas can be used to dramatically modify the optomechanical response of the mechanical resonator. We examined hybrid schemes wherein the mechanical resonator is coupled either to the motional or the spin degrees of freedom of the ultracold gas. In either case, we find an enhancement of more than two orders of magnitude in optomechanical cooling due to this hybrid interaction. Significantly, based on demonstrated parameters for the cavity optomechanical device, we identified regimes that enable the ground state cooling of the resonator from room temperature. In addition, we showed that this hybrid system represents a powerful interface for the use of an ultracold quantum gas for state preparation, sensing and quantum manipulation of a mesoscopic mechanical resonator.

We also analyzed a quantum force sensor that uses coherent quantum noise cancellation (CQNC) to beat the Standard Quantum Limit (SQL). This sensor, which allows for the continuous, broad-band detection of feeble forces, is again a hybrid dual-cavity system comprised of a mesoscopic mechanical resonator optically coupled to an ensemble of ultracold atoms. In contrast to the stringent constraints on dissipation typically associated with purely optical schemes, the dissipation rate of the mechanical resonator only needs to be matched to the decoherence rate of the atomic ensemble -- a condition that is experimentally achievable even for the technologically relevant regime of low frequency mechanical resonators with large quality factors. The modular nature of the system further allows the atomic ensemble to aid in the cooling of the mechanical resonator, as discussed above, thereby combining atom-mediated state preparation with sensing deep in the quantum regime.

4. Polariton physics and quantum heat engines

From that point on we turned much of our attention toward what can perhaps be called “polariton physics” in quantum optomechanics. While up to that point our interest concentrated primarily on the behavior of the “bare modes” of the system -- photons or phonons-- it became increasingly apparent that it is useful to think also in terms of normal modes, or polariton modes, which are coherent superpositions of the photon and phonon fields. This is because the nature of these polaritons can easily be controlled, changing them from almost perfectly photon-like to phonon-like, simply by varying an external control parameter, for instance the frequency of the driving field. Because the photons and phonons are coupled to thermal reservoirs at different temperatures, this permits to easily conceive of practical ways to realize optomechanical thermodynamic machines such as heat engines or heat pumps.

This approach is interesting not just in the context of potential device applications, but also to address more fundamental questions related to stochastic and quantum thermodynamics. General questions include

- The investigation of the consistency of macroscopic thermodynamic quantities (work, heat, entropy) with the random, erratic motion of small systems (stochastic thermodynamics);
- The study of thermodynamics at the classical/quantum interface;
- Understanding thermodynamics at quantum mechanical microscopic and mesoscopic scales, where quantum noise coexists with thermal noise;
- Developing satisfactory and experimentally relevant concepts of work and heat in a quantum context, including in the challenging case of open systems;
- Understanding the back-action of quantum measurements (e.g. on the efficiency of heat engines);
- Determining if quantum fluctuations can be exploited to provide advantages over classical fluctuations, e.g. in efficiency (squeezed vacuum, etc.), including the roles of quantum coherence and entanglement.

Quantum heat engines have the potential to exhibit intriguing properties, including the potential to outperform their classical analogues. For example, it has been shown that a quantum photo-Carnot engine can extract work from a single reservoir provided that the latter has built-in quantum coherence, and its power can be increased by noise-induced coherence. In a different situation, a trapped ion based quantum engine operating on an Otto cycle was shown theoretically to break the Carnot efficiency limit in the presence of a squeezed reservoir.

At a more fundamental level, the definition of thermodynamic quantities in the quantum context presents conceptual challenges, and for this reason much attention has been devoted to the proper definition and the quantum statistical properties of quantities such as heat, work and entropy. In closed quantum systems work may be defined in terms of a two-time measurement scheme or, in a recently proposed alternative approach, of a single projective measurement. However the situation is more challenging for dissipative quantum systems, where there are open questions regarding the definition and experimental measurements of work and heat. In this context quantum stochastic thermodynamics, like its classical counterpart, offers an interesting framework to discuss thermodynamic properties and simulate numerically the system behavior. [Note that this is really not a new area: the thermodynamic description of quantum heat engines (QHE) has been discussed at least since the early days of laser physics. But it has recently attracted much renewed interest, because the increased control achievable over microscopic and mesoscopic systems opens promising new avenues of theoretical and experimental investigation.]

Within this broad context we proposed and analyzed theoretically an optomechanical quantum heat engine (QHE) based on an Otto cycle that can help address a number of these questions in a situation that should be amenable to experimental tests in the near future. In this system the intracavity field of an optical resonator coupled to a cold reservoir represented by the cavity dissipation interacts coherently with a single mode of vibration of a mechanical resonator connected to a thermal bath at the temperature of the mesoscopic solid state device. The control of the dispersion of the QHE normal modes permits to cycle the system between the two baths at different temperatures thus realizing thermodynamic cycles via the manipulation of an external parameter such as the detuning between the driving optical field and the cavity resonance frequency. Work is performed by the photons present in the cavity via the radiation pressure exerted on the mechanical resonator, which is at the origin of the optomechanical interaction. Particular emphasis was placed on the quantum measurement of that work and its fluctuations, and also on the back-action of said measurement on the efficiency of the system We showed that for our specific QHE the work can be evaluated from repeated measurements of the intracavity photon number, which is directly proportional to the radiation pressure force.

By considering different types of measurements, specifically an absorptive and a dispersive measurement scheme, both involving passing a stream of two-state atoms through the resonator we have been able to compare and contrast important aspects of measurement backaction on the system. Absorptive measurements result in projective measurements of the photon number, and the associated coupling between the normal modes of the optomechanical system, while the dispersive measurements correspond to the addition of an additional energy dissipation channel for the photons. We numerically determined the mean work and its variance over the entire thermodynamic cycle for both measurement schemes and use these results to evaluate the measurement back-action in the thermodynamic cycle.
Our analysis was carried out within the framework of quantum stochastic thermodynamics, with the measured work evaluated via continuous detection of the mean photon number in the cavity.

In an extension of the `polariton physics' point of view in a perhaps more applied direction we also studied in some detail is a novel type of microwave detector operating at the single photon level.

One motivation for this work is that the microwave frequency domain of the electromagnetic spectrum is the stage of a wealth of phenomena, ranging from the determination of the quantum energy levels of superconductor nanostructures to the rotational modes of molecules and to the characterization of the cosmic microwave background. Several detection schemes sensitive to microwave radiation at the single-photon level have been demonstrated in the past, including semiconductor quantum dots in high magnetic fields, circular Rydberg atoms in cavity QED setups, and superconducting qubits in circuit QED. An alternative approach involves the use of linear amplifiers. These devices allow the reconstruction of average amplitudes and correlation functions, but they require the integration over many events to achieve a sizable signal. However no general purpose efficient single photon detector has been developed so far, a major challenge being that photon energies in that frequency domain are in the meV range, three orders of magnitude smaller than in the visible or near-infrared spectral regions.

On the other hand, in the optical frequency domain a variety of ultra-sensitive detectors have been developed over the past sixty years. This suggests that an alternative route for the detection of feeble microwave signals is via their conversion to the optical frequency domain. Photonic front-end microwave receivers based on the electro-optical effect and atomic interfaces based on electromagnetically induced transparency have exploited nonlinear conversion to this end. The main limitations in sensitivity are the small strength of the interaction and the fluctuations of the optical driving fields.

Several theoretical proposals have considered optomechanically mediated quantum state transfer between microwave and optical fields, with an emphasis on the potential of hybrid systems as quantum information interfaces Developments of particular relevance include the experimental realization of coherent conversion between microwave and optical field based on a hybrid optomechanical setup. Our proposal however has a different and in a sense more limited goal: it is to convert the mean intensity of a feeble, narrow-band microwave signal to an optical signal where detection can proceed by traditional methods. One key aspect of this proposed detector is that it relies on an off-resonant, multimode process. This is motivated by the need to manage and minimize the thermal mechanical noise, as well as to circumvent the effect of the fluctuations of the driving electromagnetic fields required to ensure a strong enough optomechanical coupling. These sources of noise can be significantly reduced by (i) working in a far off-resonant regime with respect to the mechanics; (ii) using pumping fields that drive ancillary cavity modes different from those at the signal frequencies, for both microwave and optical; and
(iii) exploiting the polariton modes of the cavity-mechanics system to perform the frequency conversion of the signal via a modulation of the detuning of the optical pump.

In a third application of polariton dispersion management we have analyzed a cavity optomechanical analog of a heat pump that uses a polariton fluid to cool mechanical modes coupled to a single pre-cooled phonon mode. As such this heat pump permits to cool phonon modes of arbitrary frequencies not limited by the cavity-optical field detuning deep into the quantum regime from room temperature.

One drive behind this work for this work is the interest in exploring a number of aspects of multimode phononics, as we mentioned earlier in section 2. For this purpose there would be significant benefit in cooling several modes deep into the quantum regime, with directions in mind such as the generation of nonclassical states of mechanical motion or the development of phonon interferometry. However optomechanical ground state cooling typically relies on approaches where the laser field driving the motion of the mechanical oscillator is tuned to the red side of a cavity resonance. In most cases this is applied to the cooling of a single mechanical mode. As a way to circumvent this problem our proposed polaritonic heat pump would permit to simultaneously cooling two or more modes of relatively arbitrary frequencies. The cooling cycle uses a precooled polariton mode as a ``polariton fluid'' whose nature is first changed from photon-like to phonon-like by controlling the detuning between the driving laser and the cavity mode frequency. When in the phonon-like state it is then parametrically coupled to the phonon mode to be cooled for a time such that an approximate coherent state transfer is achieved between them. Following that step the detuning is then adiabatically returned to a value for which the polariton is photon-like, where thermalization at T > 0 of the photon bath dumps the excitations carried away from the mechanics to the environment, thereby completing the irreversible extraction of energy from the mechanical mode.

Finally in our most recent work we have expanded the basic idea of polariton engineering to what is arguably the simplest quantum heat engine, a single two-state atom (or artificial atom) coupled to a single photon. In this case the polariton modes are the familiar dressed states of quantum optics. We believe that this textbook system could be demonstrated experimentally in a circuit QED environment.

Since I will now be retiring from the University of Arizona this is my last ARO report. I wrote it with mixed feelings, because I have all kinds of ideas that I still want to pursue, in particular on quantum thermodynamics (in particular on autonomous quantum heat engines) as well as on quantum sensing and on quantum acoustics more generally. But on this other hand I feel that it is time to pass the baton. Most importantly, I want to take this opportunity to thank the Army Research Office, and most particularly Drs. Peter Reynolds and Paul Baker, for their professional and uncomplicated support for so many years. It has been a pleasure and privilege to receive the kind of support and trust that they have invariably given me. Thank you in my name and in the name of my students and postdocs. This has been a great ride!

Technology Transfer